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Regional climate change experiments over southern South America. I: present climate

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Abstract We present an analysis of a regional simulation of present-day climate (1981–1990) over southern South America. The regional model MM5 was nested within time-slice global atmospheric model experiments conducted by the HadAM3H model. We evaluate the capability of the model in simulating the observed climate with emphasis on low-level circulation patterns and surface variables, such as precipitation and surface air mean, maximum and minimum temperatures. The regional model performance was evaluated in terms of seasonal means, seasonal cycles, interannual variability and extreme events. Overall, the regional model is able to capture the main features of the observed mean surface climate over South America, its seasonal evolution and the regional detail due to topographic forcing. The observed regional patterns of surface air temperatures (mean, maxima and minima) are well reproduced. Biases are mostly within 3°C, temperature being overestimated over central Argentina and underestimated in mountainous regions during all seasons. Biases in northeastern Argentina and southeastern Brazil are positive during austral spring season and negative in other seasons. In general, maximum temperatures are better represented than minimum temperatures. Warm bias is larger during austral summer for maximum temperature and during austral winter for minimum temperature, mainly over central Argentina. The broad spatial pattern of precipitation and its seasonal evolution are well captured; however, the regional model overestimates the precipitation over the Andes region in all seasons and in southern Brazil during summer. Precipitation amounts are underestimated over the La Plata basin from fall to spring. Extremes of precipitation are better reproduced by the regional model compared with the driving model. Interannual variability is well reproduced too, but strongly regulated by boundary conditions, particularly during summer months. Overall, taking into account the quality of the simulation, we can conclude that the regional model is capable in reproducing the main regional patterns and seasonal cycle of surface variables. The present reference simulation constitutes the basis to examine the climate change simulations resulting from the A2 and B2 forcing scenarios which are being reported in a separate study.

Keywords Regional climate modelling · Southern South America · Present climate

Abbreviation

GCMs	General circulation models
RCMs	Regional climate models
LSM	Land-surface model
SST	Sea surface temperature
LLJ	Low level jet
DJF	December–January–February
JJA	June–July–August
SLP	Sea level pressure

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1 Introduction

General circulation models (GCMs) are the most promising tools to determine the response of the climate system to increasing greenhouse gas concentration and to assess how the system will evolve under different emission scenarios. Nevertheless, due to the complexity of these models and the fact that they operate globally, their spatial resolution, typically of several hundred kilometres, is considered insufficient for many purposes. First of all, GCMs are not able to capture adequately the regional-scale forcing and, in consequence, they are not able to represent the small scale processes and their related heat and momentum fluxes that critically affect the broader scale circulation. Moreover, near-surface variables are strongly influenced by the spatial resolution in which the model operates.

After the pioneering works of Dickinson et al. (1989) and Giorgi (1990) the development of regional climate models (RCMs) nested into GCMs has been broadly applied for different applications and different regions. Now, it is commonly accepted that regional climate modelling is the most adequate tool to simulate regional climate with better accuracy than low-resolution GCMs. Because RCMs operate on higher spatial resolution (typically 20–50 km) they are capable of representing finer-scale details related to thermal contrasts due to complex topography or other surface inhomogeneities. Studies such as Giorgi et al. (2004), Caya and Biner (2004), Räisänen et al. (2004), show that regional climate simulations improve the representation of sensitive climatic variables, such as precipitation and near surface temperatures, when compared with the driving GCM. However, RCMs still exhibit systematic biases due to several shortcomings inherent to the methodology, such as the regional model configuration itself and issues concerning the driving boundary conditions (Liang et al. 2004; Frei et al. 2003; Seth and Rojas 2003; Moberg and Jones 2004; Giorgi et al. 2004, among others).

The results from RCM simulations over South America are relatively few. Some pioneering studies have been published such as Menéndez et al. (2003), Nicolini et al. (2002) and Figueroa et al. (1995), focused on seasonal simulations. Most recently, Misra et al. (2003) performed some seasonal simulations to explore predictability issues over tropical and subtropical South America. Seth and Rojas (2003) and Rojas and Seth (2003) performed regional simulations in order to explore the sensitivity of the regional model to domain size and surface forcing. Xu et al. (2004) explored the effect of the Andes on the eastern Pacific climate. All these studies, based on RCMs nested in global reanalysis or GCMs, provided valuable information about key concerns regarding systematic biases of regional models over the South American region.

Nevertheless, to date, there is a lack in the literature with results from a continuous long-term simulation allowing the evaluation of regional climate modelling over South America, which represents the first step to build regional climate change scenarios. As part of the Second National Communication of Climate Change for Argentina, three 10-year simulations have been completed over southern South America using the fifth-generation Pennsylvania State University-NCAR (Penn State-NCAR) Mesoscale Model MM5, nested within the Hadley Centre global atmospheric model HadAM3H (Pope et al. 2000). The simulations cover a 10-year period representing present-day climate (1981–1990) and two future scenarios for the SRESA2 and B2 emission scenarios (IPCC 2000) for the period 2081–2090. The purpose of these simulations is to analyze the regional climate change over southern South America and to create a dynamically consistent data base for impact studies. A robust evaluation of the uncertainties related to regional climate change projections should include the evaluation of uncertainties related to the methodology used to produce those projections. In this context, the reliability of the high-resolution simulation depends on the quality of the lateral boundary conditions (LBC) and the capability of the regional model to develop realistic regional characteristics of the present-day climate. Thus, as a first step towards a better understanding of the reliability of regional climate change projections an exhaustive analysis of the present-day climate simulation should be performed. This allows a comprehensive identification and possible interpretation of systematic model biases. The analysis of the reliability of the present-day regional climate simulation over southern South America is presented here while climate change scenario experiments are examined in a companion paper.

Southern South American climate and its variability are affected by both remote, regional and local forcings. The target region extends from the tropics towards the extra-tropics and high latitudes, the southernmost part of the region being embedded within the westerly circulation. Climate over the region is characterized by interactions of several dynamical processes. The most important feature of the regional geography is the complex Andes chain, which extends all along the western coast and is characterized by a narrow barrier channelling the flow in the central part of the region.

During summer the large scale circulation at upper levels is characterized by a high pressure centre over the Altiplano, a trough extending from northeast Brazil towards subtropical latitudes over the Atlantic Ocean and westerly circulation over subtropical and higher latitudes. At low levels, the semi-permanent subtropical highs over the Atlantic and Pacific oceans, dominate the large scale features. Easterly flow from the Atlantic Ocean is channelled southward by the Andes mountains into the Chaco low, which represents the main source of moisture over southern Brazil and the subtropical plains of southern South America. Over the southern part of the area, synoptic activity is dominated by the presence of the Pacific storm-track and its interaction with the Andes, thus, precipitation is largely dominated by the effect of the topography on high-frequency eddies.

During winter the recurrent passages of cold fronts progressing north-eastward east of the Andes from sub-polar latitudes and the upper level troughs propagating eastward at subtropical latitudes are the triggering factors for strong cyclogenesis over eastern South America. Enhanced moisture transport from the tropics along the eastern part of these lows favours precipitation occurrence. The presence of the Pacific subtropical high, its seasonal meridional shift and the sea surface temperature over the subtropical Pacific Ocean define the seasonal cycle of precipitation west of the Andes. The ability of the driving GCM and the regional model to capture these climatic circulation features and their relationships to moisture transport and continental rainfall will be one of the focuses of the present evaluation.

The goal of this study is to assess the capability of the regional model to simulate present-day regional climate over southern South America, with emphasis on precipitation and near-surface extreme temperatures. The analysis is mainly focused over land areas due to the availability of gridded observed datasets for model validation over a region characterized by sparse station data. The capability of the regional model in reproducing regional circulation patterns, such as low-level winds and sea level pressure (SLP) is also analyzed in order to better understand the model behaviour. We evaluate the model performance in terms of mean climatic conditions, seasonal cycles, interannual variability and extreme events.

The paper is organized as follows: Sect. 2 describes model set up and provides details on how the experiment has been designed. The data used to validate the present-climate simulation is also presented in this section. Section 3 is devoted to evaluate the model performance through the analysis of seasonal means, the annual cycle of precipitation and extreme temperatures, the interannual variability and daily precipitation statistics over selected sub-regions. Section 4 presents a discussion of possible causes for model biases and finally, Sect. 5 summarizes the conclusions.

2 Description of the model, experiment and validation data

2.1 The regional model

The regional climate simulation was performed using the fifth-generation Pennsylvania-State University-NCAR non-hydrostatic Mesoscale Model MM5 (Grell et al. 1993) version 3.6. Menéndez et al. (2003, 2004) performed a series of experiments aimed to test the capability of MM5 in simulating climate conditions over the target region, through a set of sensitivity experiments including the response to different convective schemes, surface process parameterizations and domain size, driven by "perfect" boundary conditions form the NCEP/NCAR reanalysis (Kalnay et al. 1996). Though those sensitivity experiments were relatively short, spanning no more than two months, the experience gained through these previous studies has defined the most adequate model configuration in order to capture the main climatic characteristics over southern South America.

Regional model configuration used to perform the continuous 10-year simulation includes the Kain–Fritsch convective scheme (Kain and Fritsch 1993). Among the various convective schemes tested including Grell and Kuo schemes, the Kain–Fritsch scheme consistently produces higher, and therefore, more realistic convective precipitation over subtropical South America, including La Plata basin, during summer months. Planetary boundary layer parameterization is formulated following the scheme by Hong and Pan (1996), which includes an implicit approach for vertical flux divergence, vertical diffusion in the stable atmosphere and moist vertical diffusion in clouds. Moisture tendencies were calculated by explicit moisture scheme (Hsie et al. 1984) with ice phase processes included. The calculation of radiative heating or cooling in the atmosphere accounts for long-wave and short-wave interactions with explicit cloud and clear air. The radiation package calculates long-wave radiation through clouds and water vapour, based on Stephens (1978) and Garand (1983). It also accounts for short-wave absorption and scattering in clear air and reflection and absorption in cloud layers (Stephens 1984). Surface processes are represented by Noah Land Surface Model (Chen and Dudhia 2001). The land-surface model (LSM) is capable of predicting soil moisture and temperature in four layers with thicknesses of 10, 30, 60 and 100 cm, as well as canopy moisture and water-equivalent snow depth. The LSM makes use of vegetation and soil type in handling evapotranspiration, and takes into account variations in soil conductivity and the gravitational flux of moisture.

The regional model was run in a Mercator grid with 50 km resolution (approximately) in both horizontal directions, with 93 points in the west-east and 109 points in the south-north direction. The outermost eight grid points at each side were used as boundary relaxation zones. The integration domain covers southern South America, from 15 to 55°S and from 85 to 42°W.

In the vertical 23 sigma levels were used with the model top at 50 hPa. The land-sea mask and topography have been derived from the US Navy 10-min resolution dataset. Vegetation and soil properties were obtained from USGS vegetation/land use data base.

Figure 1 displays the model topography and domain used in this study. Most of the maps shown hereafter exclude the buffer zones and two additional rows and columns of the ordinary model area where sharp gradients in precipitation due to spurious convergence at the boundaries were found.

2.2 Boundary conditions

Data from the Atmospheric GCM HadAM3H was used to drive the regional model. The HadAM3H model is a high-resolution version (1.25° latitude by 1.875° longitude resolution) of the Hadley Centre Atmospheric Global Model. Details on model configuration can be found in Pope et al. (2000). Present climate simulation performed with HadAM3H was obtained from the 1961–1990 time slice initialized with atmospheric and land surface conditions from the Coupled Atmospheric-Ocean GCM from the Hadley Centre (HadCM3) and forced with observed sea surface temperature (SST) and sea-ice distribution from the Hadley Centre HadISST dataset (Rayner et al. 2003).

The MM5 model requires initial and time evolving boundary conditions for wind components, temperature, geopotential height, relative humidity and surface pressure. These variables were provided in a 6-hourly interval within a relaxation zone in the lateral boundaries. MM5 also requires the specification of sea surface temperature (SST). SSTs are prescribed from the observed OISST data set (Reynolds el at. 2002) monthly mean values interpolated from a 1° resolution grid. Monthly fraction of vegetation cover derived from the NCEP reanalysis dataset are also prescribed over land. The land surface model coupled to the regional model also requires additional datasets for initial conditions over land. These include soil temperature and soil moisture for 2 layers below the surface (0–10 and 10–200 cm), prescribed from the NCEP reanalysis database.

2.3 Experiment design

The regional model was initialized at 00Z 1st January 1980 and the simulation extended to the end of 1990. The first simulated year is considered as spin-up period to allow stabilization of soil variables from the land surface model (Christensen 1999).

In order to evaluate maximum and minimum temperatures, we archived the MM5 output for 2-m temperature every hour, and search for the daily maximum and minimum values.

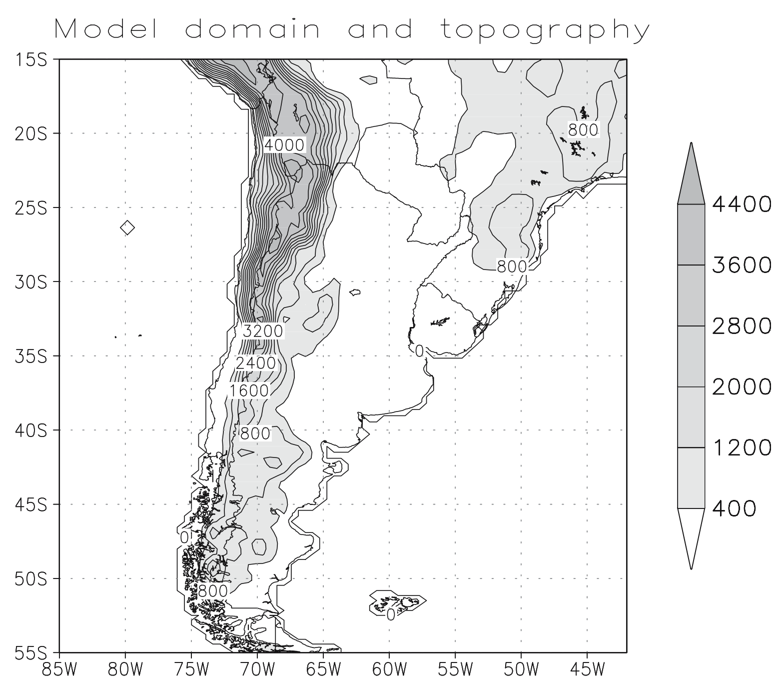

Fig. 1 Model domain and topography. Contours are drawn every 400 m. *Shading* represents topographic heights more than 400 m

2.4 Validation data

For the validation of monthly precipitation, surface mean, maximum and minimum temperatures we used the dataset compiled by the Climatic Research Unit (CRU) of the University of East Anglia (New et al. 1999, 2000). This dataset includes monthly precipitation, mean, maximum and minimum temperature data in a 0.5° resolution global grid spanning the period from 1901 to 2001. In the following analysis we compare the CRU data to the MM5 simulation as it has similar spatial resolution. In the comparison of surface variables, precipitation and surface temperatures, the CRU data were interpolated to the model grid and all fields are shown over land only.

For validating circulation variables, we used the NCEP reanalysis dataset (Kalnay et al. 1996) for the simulated period at a horizontal resolution of 2.5 degrees. We used this quasi-observational data set to evaluate the circulation fields of both HadAM3H and the regional model, in order to explore regional model uncertainties and to assess the quality of the driving model.

Another observational data set used for the evaluation of daily precipitation statistics is the gridded daily precipitation data for South America (Liebmann and Allured 2005), spanning the period 1940–2003. This dataset was constructed from station data onto a regular latitude-longitude grid of 1° resolution. The distribution of station data over South America lacks an adequate spatial coverage, thus, the gridded data base contains large areas with missing values.

3 Results

3.1 Low-level circulation patterns

Biases in the simulated regional climate are influenced by deficiencies in both the regional model formulation and LBC. Therefore it is worth to evaluate the systematic errors in the driving fields, particularly in the SLP field and winds at 850 hPa in order to understand the biases in the regional simulation. Figure 2 displays mean SLP fields for austral summer [December–January–February (DJF)] and austral winter [June–July–August (JJA)] seasons averaged over the period 1981–1990 as depicted by NCEP, HadAM3H and MM5.

In summer the subtropical high over the Pacific is slightly weaker and shifted poleward in HadAM3H compared with NCEP and the subtropical high over the Atlantic Ocean is located further south-eastward. The sub-polar low is deeper than observed, a common feature in many AGCMs. The orographically thermally induced depression over northern Argentina, the Chaco low, is not well represented in the driving model, which shows a broader low pressure system extending east of the Andes. The misrepresentation of this system may be related with the low resolution of the HadAM3H model and thus with a poor representation of topographic features. Nevertheless, the regional model is able to capture the depression, though slightly more intense and more extended into Paraguay than in the observations. In the regional model the subtropical high over the Atlantic is also more intense and shifted poleward, as in the driving model, but is closer to the continent. During winter the subtropical high over the Pacific Ocean is well represented in the HadAM3H model, though east of the Andes it shows lower pressure than in the reanalysis data. The subtropical high over the Atlantic is more intense compared with NCEP and slightly shifted poleward and the sub-polar low is deeper, thus, the meridional pressure gradient over subtropical latitudes over the south Pacific and south Atlantic Oceans are larger than in the reanalysis. SLP is underestimated in the driving model over the continental area. The regional model improves the representation of surface pressure over the continental area, though some underestimation remains south of 30°S, as in the driving model. Thus, in both models the region of strong meridional pressure gradient is shifted equatorward. Overall, the driving model presents important biases in the SLP field. Some of them remain in the regional model, though, in general, the regional model is able to improve the representation of many features of the observed patterns, in particular, those related to topography-induced circulations.

As mentioned before, the main source of moisture at subtropical latitudes to the east of the Andes comes from the north, being associated with moist advection from the tropical forest. Thus, in order to give a possible explanation to the bias in the precipitation field it is relevant to analyze the low level circulation field. Figure 3 shows 850 hPa winds from models and reanalysis.

One of the main characteristics of summer circulation over South America is the low level jet (LLJ) along the eastern slope of the Andes. The core of the LLJ is located around 850 hPa and 17°S (Saulo et al. 2000). The HadAM3H model captures reasonably well the structure of the LLJ, but the intensity of the wind is overestimated at the exit region. The misrepresentation of the Chaco low in the driving model makes the northerly flow to extend too far southward, compared with NCEP. The regional model captures the structure of the LLJ reasonably well over Bolivia, but the cyclonic circulation associated with the Chaco low is shifted north-eastward its observed position, producing enhanced easterly component over north-eastern Argentina and south-eastern Brazil. Due to this misrepresentation of the low-level circulation, the wind pattern over Paraguay, south-eastern Brazil, north-eastern Argentina

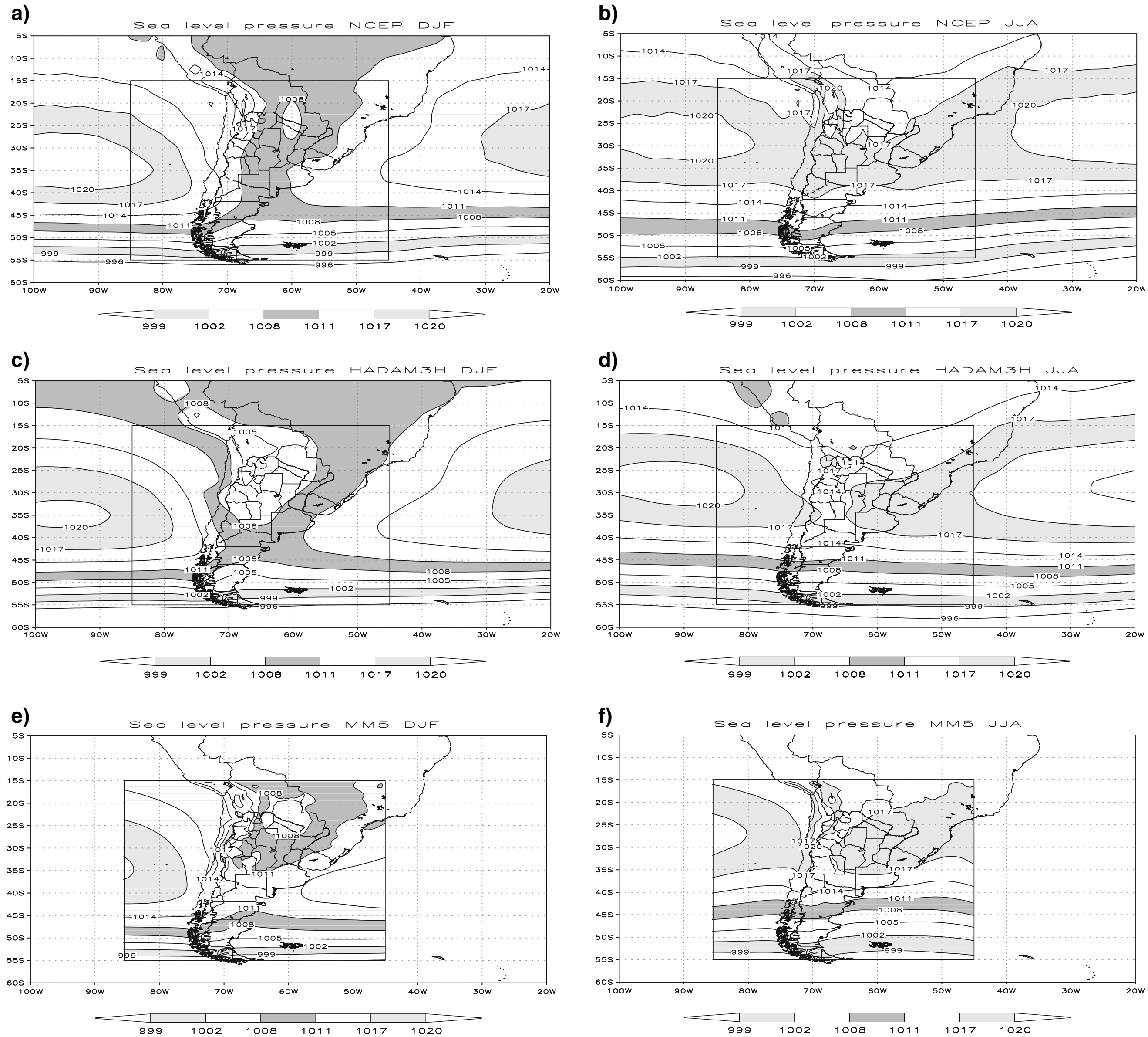

Fig. 2 Average sea level pressure (*SLP*) fields for the period 1981–1990 for summer December–January–February (DJF) (**a**–**c**–**e**) and winter June–July–August (JJA) (**b**–**d**–**f**). NCEP reanalysis data (**a**, **b**), the atmospheric GCM HadAM3H (**c**, **d**) and the regional model MM5 (**e**, **f**). Contour interval is 3 hPa. *Shadings* indicate some selected pressure intervals to highlight the spatial patterns

and Uruguay presents a large bias in the regional model. The misrepresentation of this circulation feature has a strong impact on the simulated precipitation over that region, as will be discussed later. During winter, the LLJ is also present in both HadAM3H and MM5, though the intensity of the north-westerly flow over Paraguay and north-eastern Argentina is too weak in MM5, compared with the reanalysis. At higher latitudes, between 40 and 55°S, westerlies over the western coast of South America and over Patagonia are stronger in both HadAM3H and MM5, compared with the reanalysis data. This behaviour induces more intense high-frequency systems embedded into the sub-polar storm-track (not shown).

In summary, HadAM3H reproduces the main features of the low-level circulation, but shows some important differences with observations. The regional model improves the representation of some key climatic circulation features, nevertheless, it fails in reproducing some circulation patterns that are critical in determining the precipitation in subtropical South America. The biases in the regional simulation are largely induced by the biases in the driving model, however, some of the deficiencies in reproducing the observed low level circulation patterns may be also due to deficiencies in the regional model itself. Results from a previous study conducted with MM5 driven by NCEP reanalysis data (Menéndez et al. 2004)

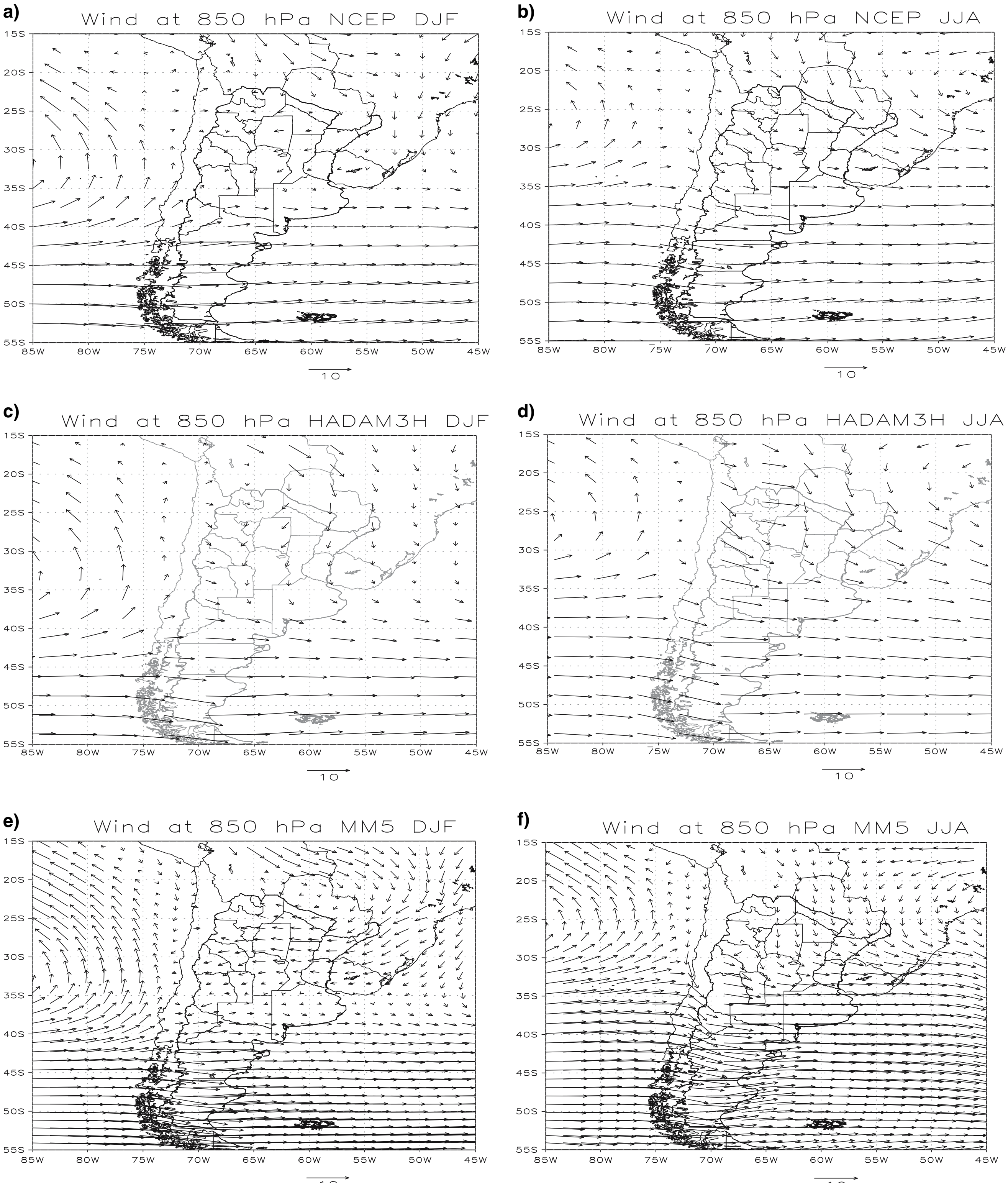

Fig. 3 Average winds (m/s) at 850 hPa for the period 1981–1990 for summer (DJF) (**a**–**c**–**e**) and winter (JJA) (**b**–**d**–**f**). NCEP reanalysis data (**a**, **b**), the atmospheric GCM HadAM3H (**c**, **d**) and the regional model MM5 (**e**, **f**)

show that some of the deficiencies in the representation of regional circulation patterns, such as the intensity of the continental low during summer months, the intensity of the Atlantic anticyclone and the meridional wind maximum in the region of the LLJ, were evident in the regional simulation nested into "perfect" boundary conditions, suggesting that they may be due to model configuration.

3.2 Surface variables

Figure 4 compares the 10-year average seasonal precipitation in CRU observations, the regional model and the HadAM3H model for austral summer (DJF) and austral winter (JJA).

During summer season, the wet season for most of South America east of the Andes, the regional model and the global model are able to represent the broad structure of the precipitation field. Both models reproduce the southwest-northeast gradient in the precipitation field. The precipitation maximum associated with the South Atlantic Convergence Zone is better captured by the regional model but slightly overestimated. The regional model tends to underestimate the precipitation over subtropical latitudes, particularly over La Plata basin and central plains.

Higher latitudes experience a large frequency of storms crossing the region, associated with the Pacific storm-track centred at 45°S inducing maximum precipitation on the western slope of the Andes. This feature is well captured by the regional and the global model but precipitation is overestimated. In both HadAM3H and MM5 westerlies are stronger than in observations, thus, synoptic activity is stronger in both models. The regional model has more detailed structure of the topography compared with HadAM3H, producing even larger precipitation amounts. This is also a common feature of regional simulations over steep mountain regions (Leung et al. 2003). Precipitation over elevated terrain areas tends to be underestimated in most databases, and direct observations are not available. Moreover, large biases also exist among observational precipitation databases in southern South

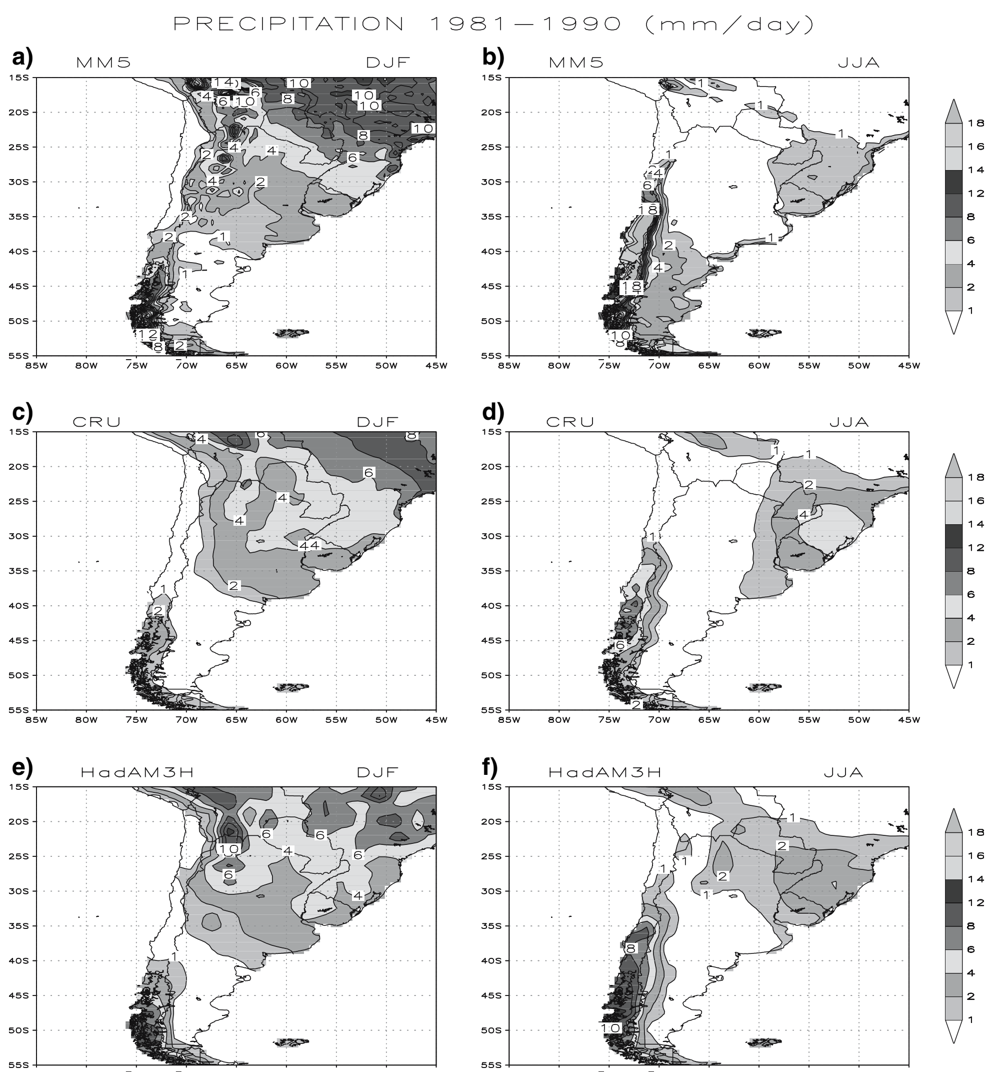

Fig. 4 Average precipitation for the period 1981–1990 from the regional model (**a**, **b**), observations (**c**, **d**) and the global model (**e**, **f**) for summer (DJF) and winter (JJA), respectively. Minimum contour is 1 mm/day. Contours are drawn every 2 mm/day for values greater than 2 mm/day

America. Comparing precipitation maps from other gridded data sets [Climate Prediction Centre Merged Analysis of Precipitation (CMAP) NOAA; Global Precipitation Climatology Project (GPCP), NASA and CRU] we found differences over mountain regions larger than 80% (not shown).

The regional and the global model are also able to capture the dry characteristics downstream the Andes.

During winter season dry conditions over most of the region are also well captured by the models. MM5 performs better than HadAM3H over subtropical latitudes, however over south- eastern Brazil, north-eastern Argentina and Uruguay the regional model underestimates the amount of precipitation and fails in reproducing dry conditions over Patagonia.

The precipitation maximum over central and southern Chile associated with the high-frequency systems evolving within the storm-track over the eastern Pacific is well captured. Nevertheless, the precipitation is overestimated in MM5 due to the stronger westerlies (coming from HadAM3H in the western boundary) interacting with steep slopes on the western side of the Andes chain. Overall, both models capture the broad spatial pattern of precipitation. The regional model performs better than HadAM3H over the west coast of South America and subtropical latitudes, but it is not able to capture adequately rainfall amounts over south-eastern South America.

Quantitative estimates of the models' precipitation biases and a more detailed analysis of its mean annual cycle can be obtained from Fig. 5, which presents simulated and observed precipitation averaged over several sub-regions defined in Fig. 6. Both modelled precipitation values were calculated taking into account land-only grid points. Precipitation from HadAM3H was interpolated to the MM5 grid.

The shape of the annual cycle of precipitation agrees in both models and all regions reasonably well with observations. Over Central Andes (CA), Altiplano (AL), Cuyo (CU), Paraguay (PA) and South-eastern Brazil (SEB), where precipitation reaches its maximum during summer and its minimum during winter, rainfall is overestimated during summer months and a better agreement is found during winter months, thus, the amplitude of the annual cycle is overestimated by the regional model. Moreover, the regional model tends to produce more precipitation than HadAM3H during the rainy season. During summer months, when the differences between the two models are the largest, precipitation in the northern parts of the model domain is mainly convective. La Plata Basin (LPB) and Southern Brazil (SB) are the regions where both models have most difficulties in simulating the annual cycle of precipitation. In LPB, the annual cycle of rainfall is characterized by two peaks, during April and November. Neither the regional nor the global model are capable of reproducing this characteristic. The major shortcoming of the regional model in this region is the systematic underestimation of rainfall in all months, but particularly in the transition seasons. Over SB, where rainfall cycle presents two peaks during February and November, with small annual amplitude, the regional model underestimates rainfall during winter months and overestimates rainfall during summer months, thus, the annual amplitude is overestimated. Over Southern Pampas (SP) and South-eastern Pampas (SEP) regions, characterized by a minimum during winter months and peaks during March and October, both models represent adequately the annual cycle, though they are not able to capture the onset of the rainy season during October. Over southern regions, such as Subtropical Andes (SUA), Southern Andes (SA) and Argentinean Patagonia (AP), the annual cycle presents a maximum during winter months. Both models represent the annual cycle but overestimate the winter maximum. High topography over the western part of the Andean regions may be affecting CRU observations, which may underestimate the actual rainfall. The difference between the two models may be caused by the higher resolution in the regional than in the global model, which enhances the topographic forcing, inducing larger overestimation in the higher resolution simulation.

In general, the regional model performs as well as the global model in simulating rainfall amounts and annual cycles over most of the sub-regions, though some difficulties are evident. It is important to remark that over some sub-regions, mainly over subtropical latitudes, the HadAM3H model seems to agree better with observations than the regional model, particularly during summer months. This apparent improvement in model behaviour is not due to a better representation of the regional circulation features associated with rainfall, but more due to a compensation of model errors in the GCM.

Besides the evaluation of mean precipitation, we also analyse the ability of the regional model in simulating high-frequency precipitation statistics, in terms of precipitation frequency and extreme events. With this assessment we pursue to evaluate how much added value involves using a regional model over the region.

Inspection of the frequency of wet days (Fig. 7), calculated as the number of days per season with rainfall amounts greater than 0.1 mm, reveals that during summer the regional model simulates more rainy days all over the model domain, except over the central Andes. The largest overestimation (by more than 20 wet days per season) with respect to CRU observations is found over Paraguay and Bolivia. This can be associated with the convective scheme used in this simulation, the Kain–Fritsch scheme, which tends to overestimate the number of rainy days. Sensitivity

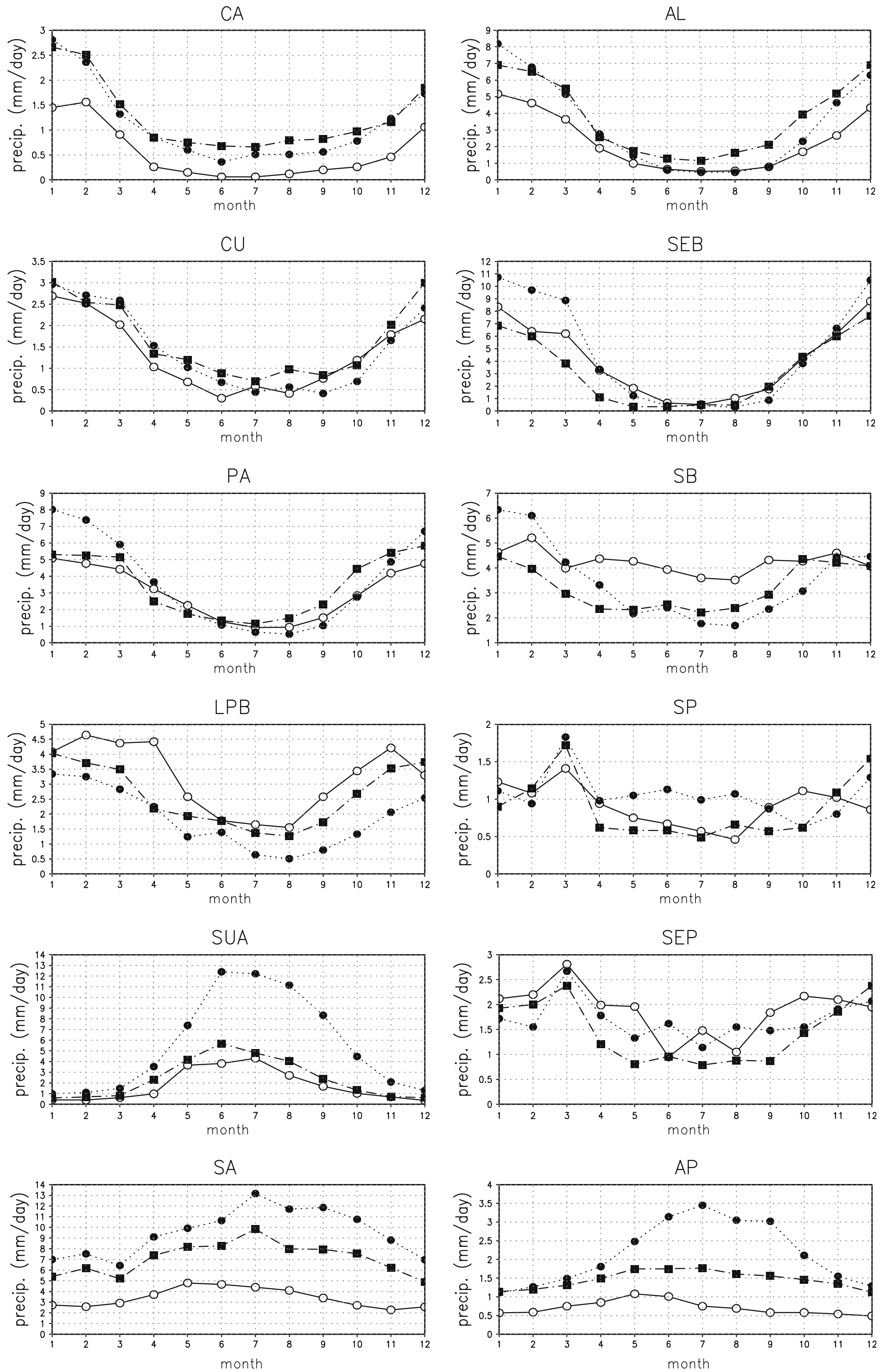

Fig. 5 Observed and simulated annual cycle of precipitation averaged over the 12 sub-regions of Fig. 6. Solid line with white circles for CRU observations; dotted line with black circles for MM5 simulation; *dashed-dotted line with black squares* for HadAM3H simulation. Units are mm/day

experiments with MM5 performed over South Africa have shown that the Kain–Fritsh scheme simulates too many rainy days (Tadross et al. 2006) thus, the positive bias in precipitation may be in part due to a positive bias in the wet day frequency. Nevertheless, this scheme was preferred among others that systematically underestimated precipitation over subtropical South America. Thus, the overestimation of rainfall in that region can be associated to both, the enhanced cyclonic circulation and the effectiveness of the convective scheme over the region.

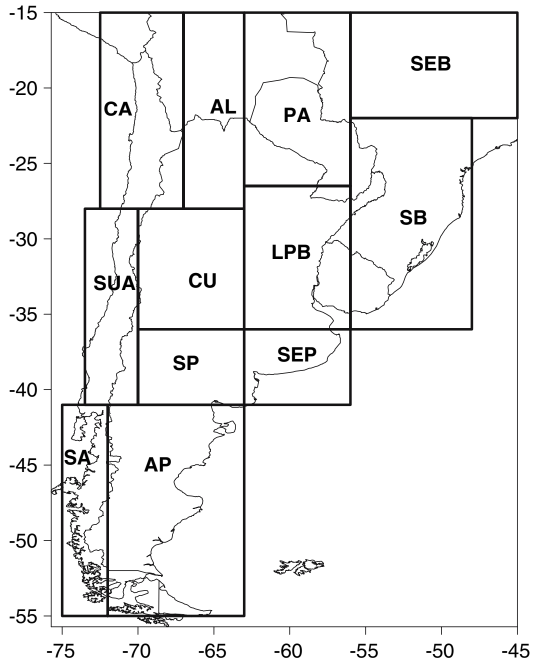

Fig. 6 Sub-regions used for a more detailed analysis of the annual cycle for precipitation. *CA* Central Andes; *AL* Altiplano; *PA* Paraguay; *SEB* South-eastern Brazil; *SUA* Subtropical Andes; *CU* Cuyo; *LPB* La Plata Basin; *SB* Southern Brazil; *SP* Southern Pampas; *SEP* South-eastern Pampas; *SA* Southern Andes; *AP* Argentinean Patagonia

The simulated number of rainy days is also overestimated in the Andes region south of 35°S, thus, the overestimate in rainfall is consistent with stronger westerlies inducing larger number of rainy days and more intense rainfall. Over central Argentina, the bias in wet days is also positive (10–20 days more than in CRU), though the total rainfall amount is less than the observed. In addition to the weaker moisture flux from the north, the underestimate in summer precipitation is likely affected by an underestimate in soil moisture. The effect of soil moisture on precipitation is a positive feedback. Drier soils contribute to weaker latent heat release from the surface and thus rainfall may be underestimated due to less intense although more frequent precipitation events.

During winter season the frequency of rainy days is underestimated over La Plata basin and Southern Brazil. The negative bias in precipitation is likely associated with the availability of moisture due to deficiencies in the position of circulation patterns.

The HadAM3H model is not able to reproduce the observed patterns of wet - day frequency. Large overestimation is evident during both seasons.

Overall, the regional model is capable of reproducing better than the global model the number of rainy days.

One of the issues of major concern of long-term climate change is the change in frequency and intensity of extreme events, particularly those associated with floods and droughts. It is expected that regional simulations improve the representation of extreme events, compared with GCMs.

Extreme precipitation events in this study are represented by the 95th percentile of daily precipitation, based on station data, the regional simulation and the global model. A threshold of 0.1 mm day^{-1} is used to select rain days for the estimation of the 95th percentile. Because the station data base used to calculate daily precipitation statistics does not cover the entire region of the simulation, we only show the results for some selected sub-regions. Figure 8 compares seasonal mean precipitation, the 95th percentile and precipitation frequency, based on simulations and station data. Results from CRU data base have also been included for the latter.

Over the northern regions, AL, PA, the frequency of wet days is overestimated by the regional model, mainly during the rainy seasons (by 40 and 30%, respectively) though much better represented than in the global model, as pointed out previously. The regional model underestimates the heavy rainfall amounts in all seasons (30%, on average), though extremes are much more underestimated in the global model. Overall, positive biases in mean precipitation over these regions are largely due to more rainy days, though less intense extreme events. Over SEB the wet bias during DJF is mainly associated with an overestimation of the heavy rainfall amount. The regional model reproduces daily precipitation statistics very well for almost all seasons and it improves the representation of extremes when compared with HadAM3H. Over SB, the regional model overestimates the mean precipitation during DJF mainly due to simulating more intense extreme events and more wet days, though the biases of both indices are relatively small (less than 5%). The underestimation of mean rainfall during MAM, JJA and SON is due mainly to underestimation of heavy rainfall amounts of around 20%. Wet day frequency is well simulated in all seasons. Dry biases over LPB region are largely due to strong underestimation of heavy rainfall amounts, particularly during the rainy season (MAM and SON) when the mean rainfall and the heavy precipitation amount are less than 50% of the observed values. However, the regional model captures the annual cycle and the magnitude of wet day frequency.

For all the sub-regions analyzed, daily precipitation statistics are better simulated in the regional model than in the global model. These metrics of daily rainfall are extremely important when regional model simulations are input for impact studies, such as biological or hydrological models in which, not only the mean precipitation, but also the daily evolution should be properly represented.

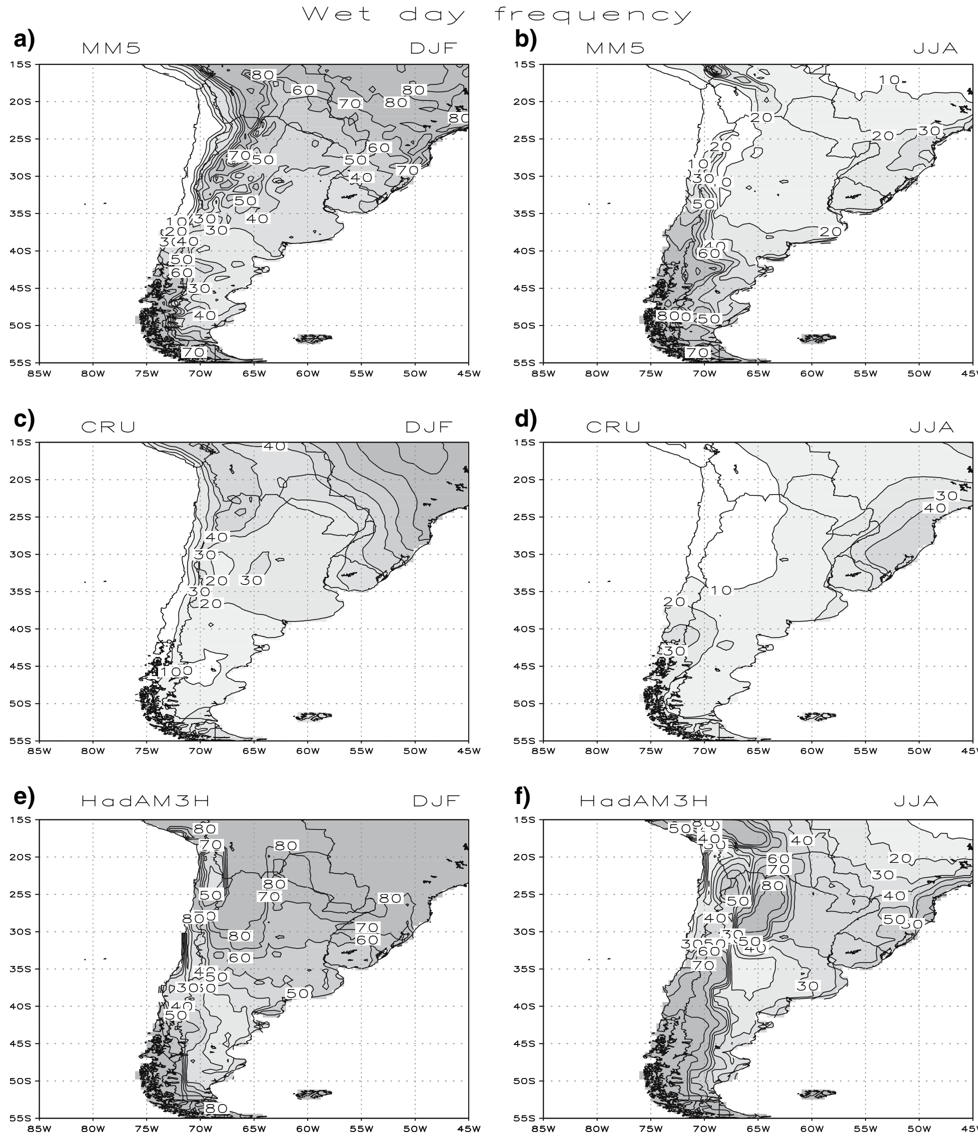

Fig. 7 Average wet day frequency (days per season) for the period 1981–1990 from the regional model (**a**, **b**), observations (**c**, **d**) and the global model (**e**, **f**) for summer (DJF) and winter (JJA), respectively. Contour interval is 10 days

To summarize the models' performance we compare annual mean differences between modelled and observed precipitation, wet day frequency and 95th percentile over sub-regions for both models in Table 1.

As noted previously the regional model improves the representation of precipitation statistics over most of the regions, compared with the global model. This is particularly evident for daily precipitation statistics.

The ability of the models to reproduce the observed interannual variability of the precipitation has also been analyzed. Interannual variability has been calculated as the standard deviation normalized by the mean precipitation, thus, the precipitation coefficient of variation is actually evaluated. Table 2 shows the coefficient of variation for DJF and JJA, averaged over sub-regions, as derived from observations, the regional model and the HadAM3H model, respectively.

The observed coefficient of variation shows larger values for winter months than for summer months over the subtropical regions (LPB, SB, AL, PA and SEB). Both models capture this seasonal variation. However, the regional model tends to overestimate the interannual variability during summer months and also produces more variability than the global model. This behavior is in agreement with results from Giorgi (2002) who discussed the scale dependence of interannual variability. He showed that during summer months the mesoscale forcing has an important role on regulating the simulated interannual variability, while during winter months simulated interannual variability is mostly regulated by boundary forcing fields.

Over the southern and mountainous regions (SA, AP, SUA), there are small differences between summer and winter in the observed variability. This feature is also captured by the models, except over SUA where both the

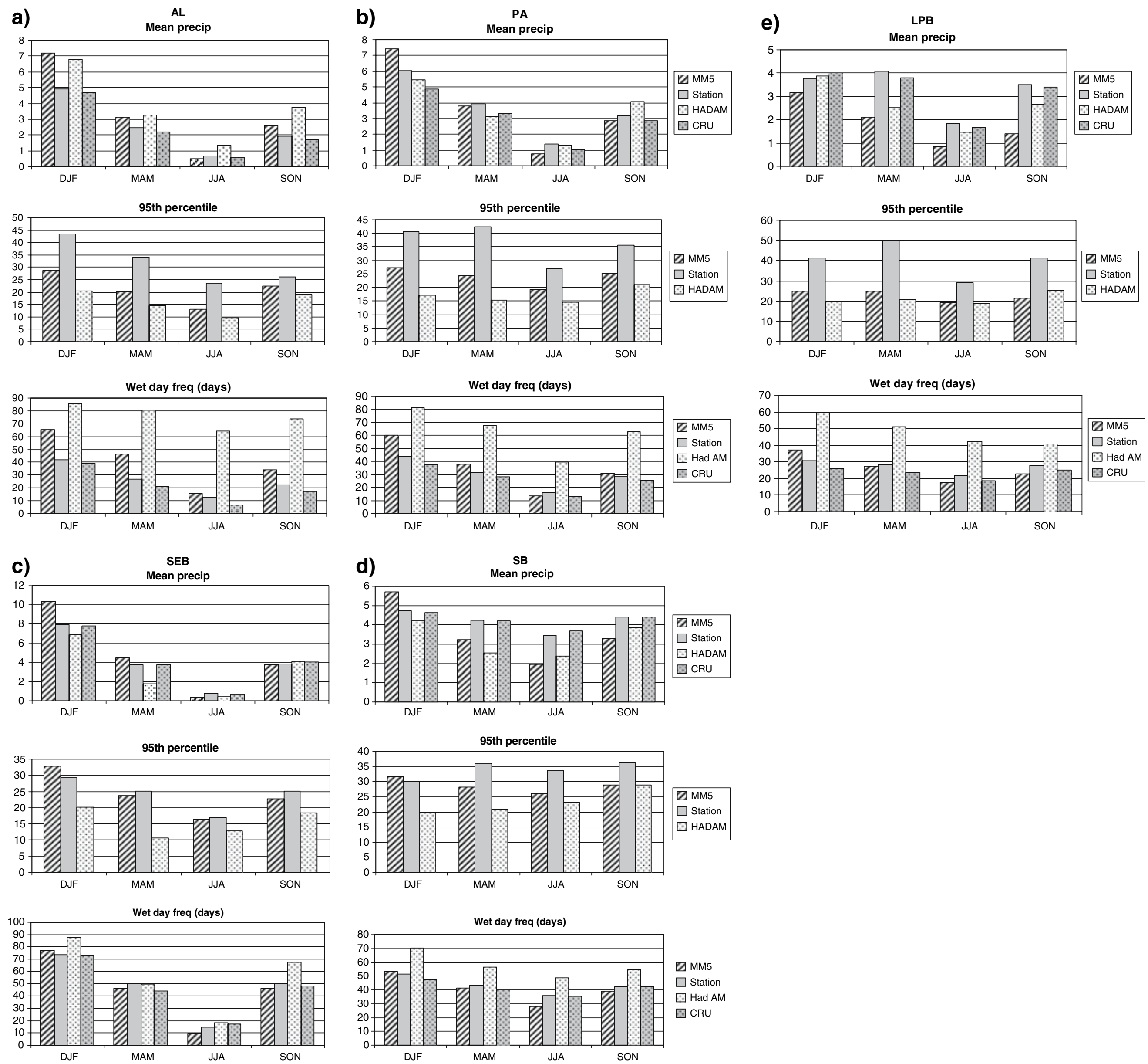

Fig. 8 Seasonal mean precipitation (mm/day), 95th percentile (mm) and wet day frequency (days) averaged over sub-regions: **a** AL; **b** PA; **c** SEB; **d** SB and **e** LPB. *Shaded bars* for station data; *shaded with black dots* for CRU observations; *white with black dots* for HadAM3H and *black and white lines* for MM5

regional and the global model show larger values during summer than during winter months. The precipitation interannual variability in the regional model over SUA is mostly driven by the HadAM3H simulation of the Pacific storm-track. Thus, the overestimation of interannual variability in the global model forces larger values in the regional model.

Overall, both models show a general good agreement with observations.

Figure 9 compares the 10-year average seasonal surface air temperature from the regional model, the global model and CRU observations. The regional model represents better than the global model the broad structure of the temperature field, particularly during summer months. Some systematic biases are found, such as a warm bias over central and northern Argentina, more intense during summer months, a cold bias over mountainous regions, and cold bias over tropical latitudes. Inspection of soil moisture fields (not shown) reveals that particularly in summer, soils are too dry over subtropical regions of southern South America, thus, drier soils and less rain over subtropical latitudes may induce higher surface air temperatures (Pal and Eltahir, 2001).The warm bias over the central plains of subtropical South America is a common feature obtained in

Table 1 Comparison of the annual mean regional model (MM5) and the global model (HAD) biases for mean precipitation (mm/day), wet day frequency (number of days per season) and the 95th percentile of daily precipitation (mm) over sub-regions defined in Fig. 6

Regions	Mean precipitation		Wet day frequency		95% percentile	
	MM5	HAD	MM5	HAD	MM5	HAD
SA	6.1	3.6	55.8	63.5		
AP	1.4	0.7	30.3	34.6		
SUA	3.8	0.6	20.0	33.9		
SP	0.1	0	9.6	16.1		
SEP	–0.1	–0.4	9.2	20.6	–10.7	–15.2
CU	0.1	0.3	12.2	35.3		
LPB	–1.3	–0.6	2.9	25.0	–17.8	–19.2
SB	–0.6	–0.9	–0.8	16.4	–5.2	–11.0
CA	0.5	0.7	–0.1	35.2		
AL	1.1	1.4	19.2	54.9	–10.7	–16.0
PA	0.7	0.4	9.4	37.0	–12.0	–19.0
SEB	0.6	–0.8	–1.0	10.0	–0.2	–8.5

Table 2 Observed (CRU) and simulated (MM5 and HadAM3H) seasonal precipitation interannual coefficient of variation for DJF and JJA, averaged over sub-regions defined in Fig. 6

Regions	Coefficient of variation					
	CRU		MM5		HAD	
	DJF	JJA	DJF	JJA	DJF	JJA
SA	0.39	0.35	0.34	0.30	0.37	0.34
AP	0.52	0.55	0.52	0.47	0.55	0.51
SUA	0.68	0.66	0.91	0.48	0.81	0.57
SP	0.65	0.72	0.73	0.68	0.61	0.88
SEP	0.45	0.64	0.70	0.67	0.45	0.68
CU	0.51	1.01	0.60	0.90	0.42	0.66
LPB	0.49	0.73	0.67	0.85	0.37	0.60
SB	0.42	0.61	0.52	0.64	0.39	0.49
CA	0.47	0.43	0.98	1.15	0.44	0.77
AL	0.37	0.79	0.41	0.99	0.25	0.68
PA	0.39	0.77	0.35	0.87	0.26	0.68
SEB	0.30	0.92	0.34	1.03	0.29	1.34

several climatic simulations for the region (Misra et al. 2002, 2003).

One last consideration regarding the temperature fields is the cold bias over mountainous regions. This is a common feature of regional climate simulations over different regions of the world (Giorgi et al. 2004). These authors point out that station data over elevated regions may be affected by a warm bias due to the predominance of stations over less elevated areas (New et al. 2000) and thus, the observed temperature may be underestimated over these regions.

The spatial structure of both maximum and minimum temperature fields is similar to the mean temperature pattern. In order to highlight the model biases in these variables we show in Fig. 10 the differences between simulated and observed fields. Maximum and minimum temperatures from HadAM3H are not available. The spatial pattern of bias for the maximum and the mean temperature is similar. For both seasons a warm bias over central and north-eastern Argentina is more pronounced in the maximum temperature than in the mean temperature, as a consequence of the impact of drier soils and less rainfall. Over southern Brazil and Paraguay, wetter conditions also induce a more pronounced cold bias. During winter months rainfall is overestimated in Patagonia and a cold bias occurs in this area, but this is mostly less than 2°C in magnitude.

Minimum temperature is overestimated for both seasons almost in the entire domain. The overestimation is larger for winter months, except over south-eastern Brazil and Paraguay. Over high mountain regions the bias is negative, as found for mean and maximum temperatures. The spatial distribution of minimum temperature bias is similar to the spatial distribution of the frequency of rainy days bias. The maximum (minimum) temperature is, in general, better represented during winter (summer) months. Though the biases are large, similar differences have been found in climate simulations over Europe (Moberg and Jones 2004).

The seasonal cycle of mean, minimum and maximum temperatures over some sub-regions is presented in Fig. 11. The choice of the regions (Fig. 12) used to evaluate them is motivated by the analysis of the projected climate change in the companion paper.

The seasonal cycle of mean temperature is well reproduced over all regions. A warm bias is observed during all months over SESA, CARG and PAT, with larger values during the cold season, smaller than 3°C on average. Over ST region, the regional model tends to underestimate the mean temperature during the first half of the year. The seasonal cycle for maximum temperature is, in general, better represented than for minimum temperature. Biases in maximum temperatures are mostly positive, except over ST and PAT regions. This behaviour may be associated with the wet bias reported over those regions. The annual cycle for minimum temperature has smaller amplitude than the observed. Minimum temperature overestimation is mainly associated with overestimation in wet day frequency.

A quantitative summary of the models' performance in terms of temperature is shown in Table 3 where we compare annual mean differences between modelled and observed temperatures over sub-regions for both models.

The regional model improves the representation of mean temperature over some of the regions, compared with the global model. The annual mean biases for mean

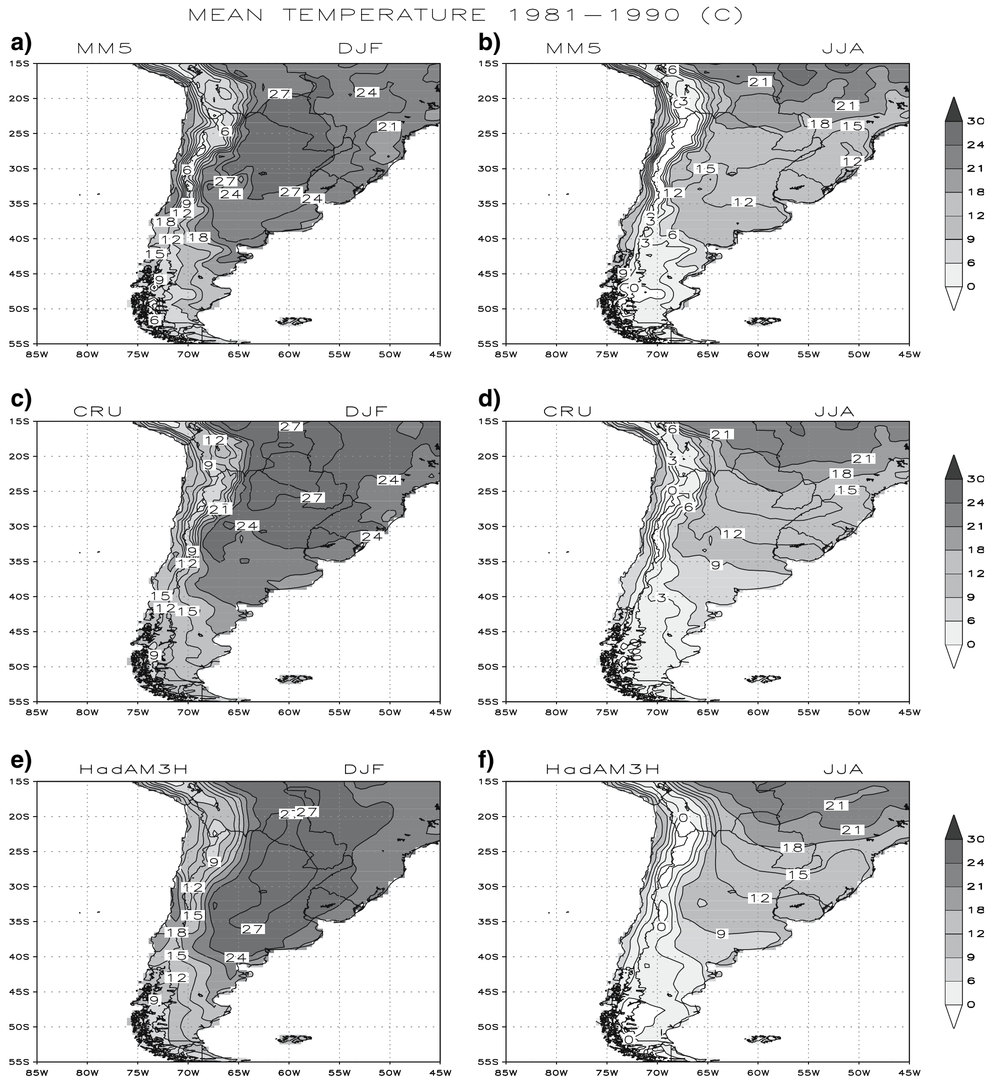

Fig. 9 Average surface air temperature for the period 1981–1990 from the regional model (**a**, **b**), observations (**c**, **d**) and the global model (**e**, **f**) for summer (DJF) and winter (JJA), respectively. Contour interval is 3°C

temperature are the smallest and for minimum temperature are the largest.

4 Discussion of simulation errors

In previous sections a detailed evaluation of the regional model simulation and the comparison with the performance of the driving global model was presented. Although the main features of the regional climate over southern South America were captured by the regional model, there are some biases which can be related to both deficiencies in the regional model configuration and deficiencies in the boundary conditions. Nevertheless, from the results presented here, it is difficult to attribute regional simulation biases to one or another.

The driving model, though simulating the broad structure of the circulation reasonably well, presents important deficiencies in the simulation of some key patterns, such as the cyclonic circulation over northern Argentina and the structure of the Low-level jet during summer months. The regional model improves these regional circulation features, mostly due to a better representation of the orography, nevertheless, the location and intensity of this topographically-induced systems are not well simulated. Moisture supply from the tropics towards subtropical South America is mainly conducted by these low-level circulation patterns. In consequence, errors in the simulated rainfall are largely related to the misrepresentation of these low-level circulation features. Summer precipitation over subtropical latitudes is largely determined by low-level convergence and moisture advection that is also strongly influenced by the South Atlantic anticyclone (Lenters and Cook 1995). Misrepresentation of the location of the subtropical high over the Atlantic Ocean in the HadAM3H model, which is inherited by the regional model, may also cause incorrect moisture flux convergence which affects the precipitation pattern. The misrepresentation of both the

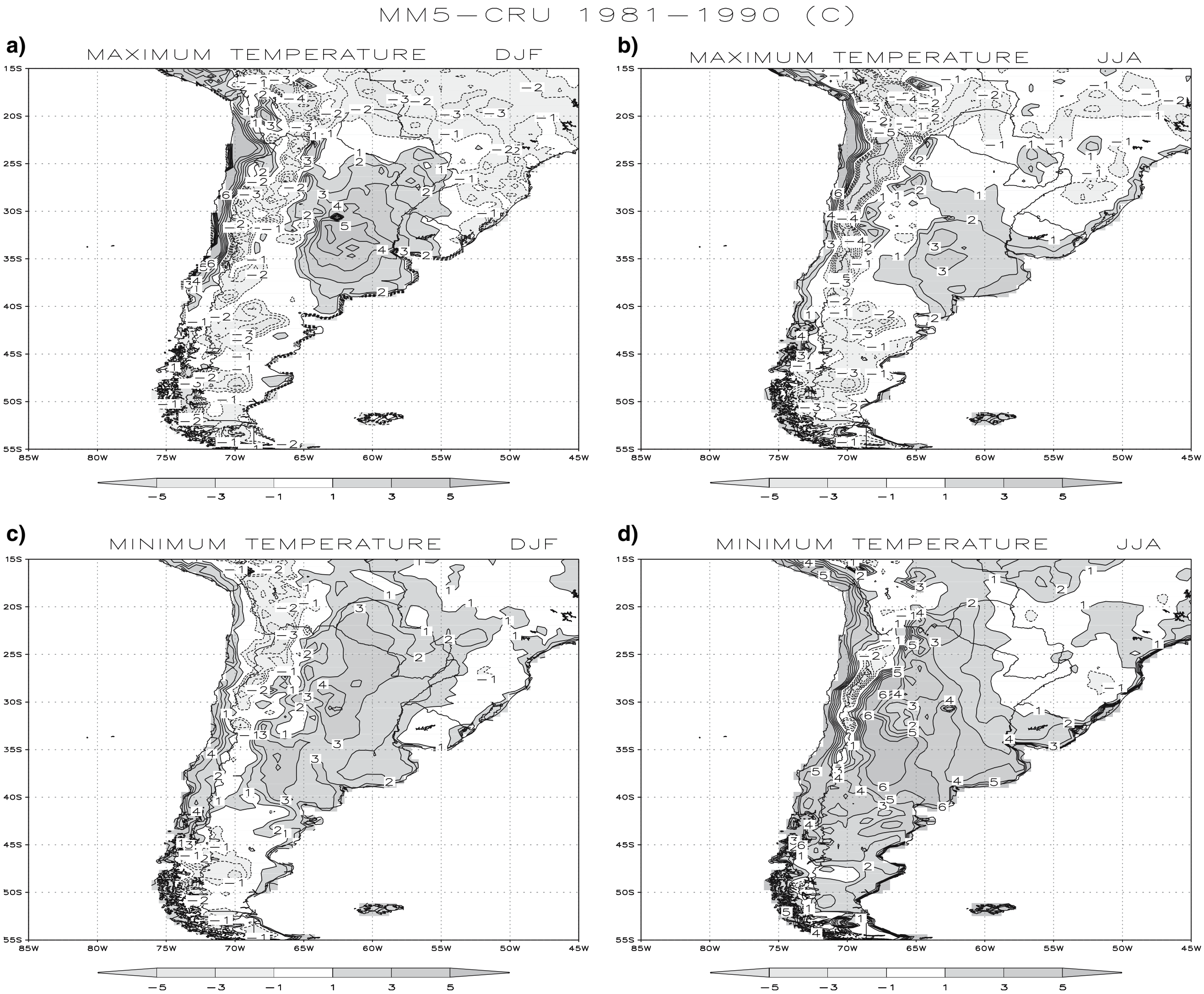

Fig. 10 Difference between MM5 and CRU for maximum temperature (**a**, **b**) and minimum temperature (**c**, **d**) for DJF and JJA, respectively. Contour interval is 1°C. *Light shading* indicates negative and *dark shading* indicates positive biases exceeding 1°C in magnitude

position of the subtropical high over the Atlantic Ocean and the regional circulation over northern Argentina in the regional model, largely determined by the forcing at the boundaries, affect the moisture advection over La Plata basin and, in consequence, rainfall is underestimated over the region. A similar behaviour has been reported in Rojas and Seth (2003).

In order to understand some of the biases in the precipitation fields, the biases in the simulated number of rainy days were explored. These biases are related to both deficiencies in the representation of surface processes and convective processes, being both possible tracks for model improvement.

Overestimation of rainfall over Paraguay and southern Brazil, particularly during summer months, may be related to different causes. First, the regional model overestimates and misplaces the low pressure centre over north-eastern Argentina, which induces anomalous moist advection. Besides this, larger wet-day frequency reveals that rainfall may be overestimated also due to the efficiency of the convective scheme, producing more rainy days than in the observations.

West of the Andes Mountains, overestimation of rainfall is related mainly to biases in the boundary conditions, which tend to produce too strong westerlies, and, in consequence, enhanced synoptic scale variability over the Pacific storm-track. Moreover, the regional model has a better representation of the orography due to higher horizontal resolution, compared with the driving model. The higher the orography in the regional model compared with HadAM3H produces more rainfall (and more rainy days) over the region.

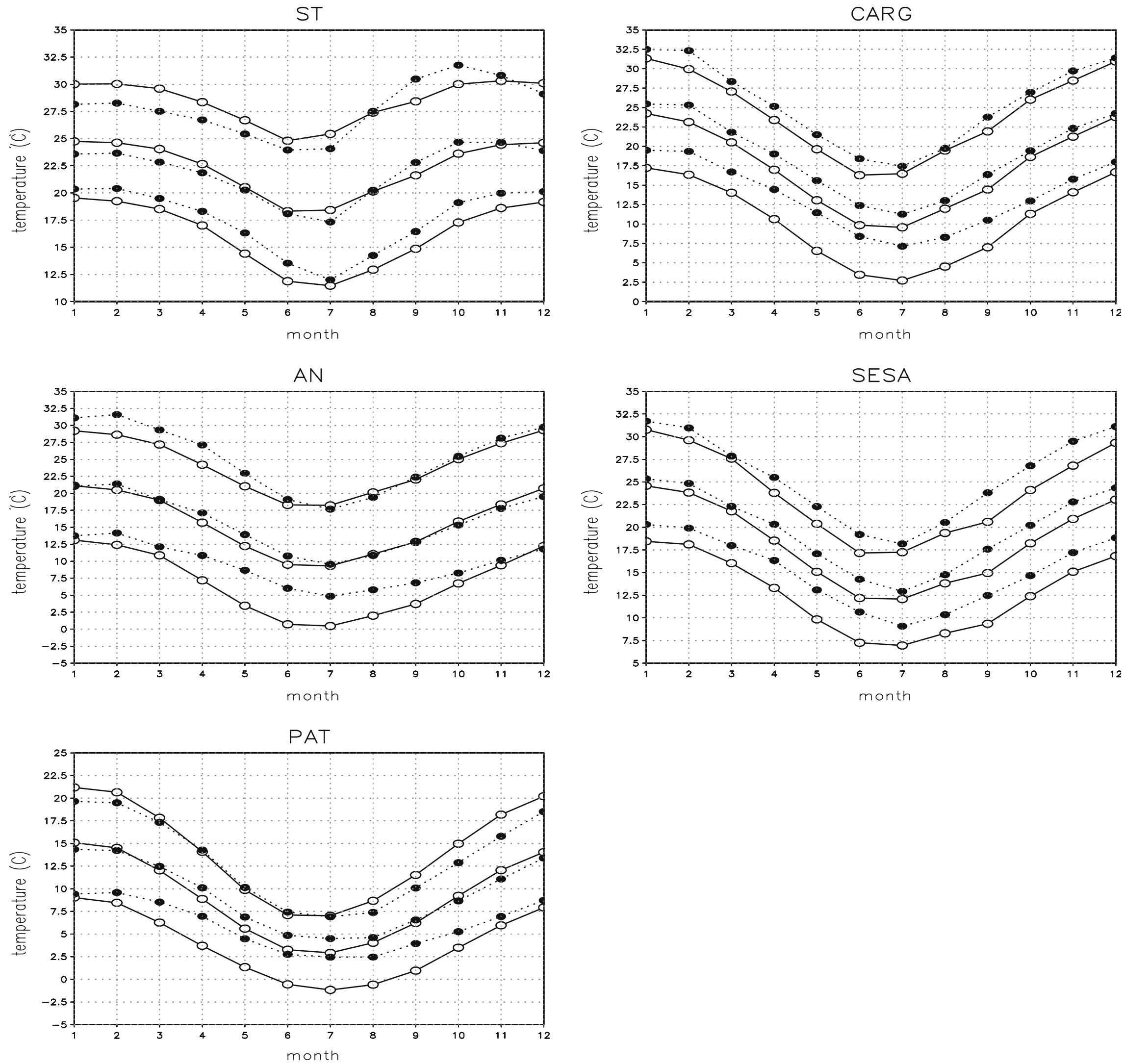

Fig. 11 Observed and simulated annual cycle of mean, maximum and minimum temperature averaged over the five subregions of Fig. 12. *Solid line with white circles* for CRU observations; *dotted line with black circles* for MM5 simulation. Units are °C

Biases in mean and maximum temperatures are consistent with biases in precipitation, negative (positive) biases are found over regions where rainfall is overestimated (underestimated). Moreover, there is a good agreement between biases in wet day frequency and biases in minimum temperature. A common factor with other regional modelling efforts over different regions of the world is that the warm biases in summer frequently occur in association with too little precipitation and soils too dry (Moberg and Jones 2004). Deficient precipitation may be associated with soils too dry and low evaporation rates, which enhances the warming of the near-surface air temperatures.

While some of the deficiencies in the regional model simulation are strongly linked to deficiencies in the boundary conditions, some of the biases in temperature and precipitation discussed here were also reported in a previous study in which MM5 was driven by reanalysis. Menéndez et al. (2004) reported deficiencies in the simulated surface air temperature and precipitation over northern Argentina, Paraguay and southern Brazil as well, thus, under "perfect" boundary conditions, the regional model itself also fails in reproducing some characteristics of the observed climate. Similar deficiencies in other modelling studies in South America are found in the literature. For instance, Misra et al. (2003) also found strong underestimation of summer rainfall over La Plata basin and overestimation over southeastern Brazil. They also found a strong overestimation of surface temperature over subtropical South America.

5 Summary and conclusions

This study presents the results from a regional climate simulation of the present-day climate, corresponding to the

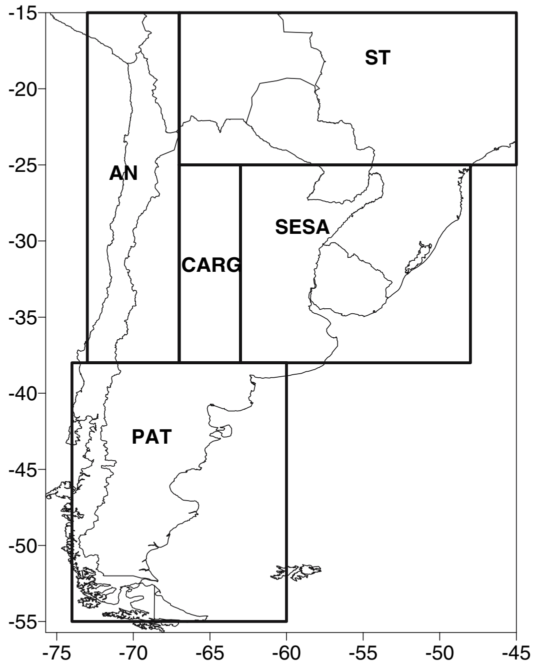

Fig. 12 Sub-regions used for a more detailed analysis of the annual cycle for mean, maximum and minimum temperatures. *ST* subtropical; *AN* Andes; *CARG* Central Argentina; *SESA* South-eastern South America, *PAT* Patagonia

Table 3 Comparison of the annual mean regional model (MM5) and the global model (HAD) biases for mean, maximum and minimum temperature (°C) over sub-regions defined in Fig. 12

Regions	Mean temperature		Maximum temperature	Minimum temperature
	MM5	HAD	MM5	MM5
AN	0.1	–0.1	0.8	1.9
ST	–0.4	–0.9	–0.6	1.2
SESA	1.3	0.6	1.7	2.4
CARG	1.4	0.1	1.3	3.1
PAT	0.2	–0.4	–0.9	2.2

period 1981–1990, over southern South America, using the MM5 RCM nested within a high resolution version of the Hadley Centre global atmospheric model HadAM3H. The analysis of the simulation is focused on evaluating the capability of the nested modelling system in representing spatial patterns of seasonal mean climate, its annual cycle, precipitation interannual variability and extreme precipitation events, with two main objectives. First, to assess the feasibility to produce useful estimates of regional climate change projections and to evaluate the added value of using a regional model. This simulation is the basis to examine the climate change simulations resulting for the A2 and B2 forcing scenarios which are reported in a separate study. Second, to identify critical aspects of regional climate simulation over a barely unexplored region.

The regional simulation reproduces many mesoscale climate features that are triggered by regional forcings, not well captured by the low-resolution driving model. Overall, the regional model improves the representation of the mean climate upon the GCM in many aspects. The first feature to note is that the regional model exhibits a better performance in the representation of the low-level circulation, not well represented in the driving model, such as the topographically induced low level cyclonic circulation during summer months over northern Argentina. Nevertheless, it fails in reproducing the correct position of the low pressure system, and, in consequence, this results in a large bias in the precipitation field. The misrepresentation of this system induces a poor representation of the low-level jet, which is critical in determining summer precipitation in subtropical South America, as it serves as conduit of moisture supply from the Amazon basin. The uncertainties in this circulation feature can cause discrepancies in the moisture budget in excess of 50% (Wang and Paegle 1996). Thus, much of the deficiency in the simulation of rainfall may be caused by the deficiency of the regional model in simulating this pattern.

The seasonal mean spatial patterns of surface variables agree reasonably well with observations, though some model biases have been identified, particularly for some specific sub-regions. For precipitation, biases in the simulation include overestimation over the Andes steep orography, underestimation over La Plata basin during fall and spring, and overestimation over Paraguay and southern Brazil during summer and fall. Biases over steep orography are due to both deficiencies in the LBC and the regional model itself. Overestimation of precipitation is a common behaviour in regional simulations over elevated terrain (Leung et al. 2003; Nicolini et al. 2002; Giorgi et al. 2004). The data used to evaluate model performance may also be biased, particularly over mountainous regions, where precipitation is usually underestimated, making it difficult to evaluate the model performance properly.

Overestimation of precipitation over Paraguay and southern Brazil may be a consequence of the positive bias in the number of rainy days, associated with the Kain–Fritsch convective scheme (Tadross et al. 2006). Similar biases in precipitation using this convective scheme have been reported by Liang et al. (2004) in a climate simulation with MM5 over North America.

Desptite the difficulties of the regional model in representing adequately rainfall amounts over some regions, it improves the representation of daily statistics, such as wet day frequency and the 95th percentile over most of the regions, compared with the global model.

The regional model tends to overestimate the interannual variability of precipitation, particularly during summer months, compared with both HadAM3H and the observations. This result is consistent with Giorgi (2002) where the scale dependence of interannual variability was discussed. Interannual variability is strongly regulated by boundary conditions during winter months. In summer, mesoscale processes play an important role in regulating the simulated interannnual variability.

The regional model simulates the observed mean, minimum and maximum temperatures quite realistically all over the model domain except over central Argentina, where a warm bias, mostly less than 3°C, is present. This warm bias coincides with a dry bias in soil moisture content. The regional model performance is generally better during the cold season, while larger biases are found during the warm season. Our analysis also reveals that biases in maximum temperature are smaller than biases in minimum temperature. Moreover, the spatial pattern of maximum temperature biases is consistent with biases in mean temperature and the precipitation field, except during winter season. The spatial pattern of biases in the minimum temperature is in agreement with the spatial pattern of biases in wet day frequency. Although there seem to be no consensus on what causes for these temperature biases are, warm biases are usually found over regions where precipitation amounts are underestimated, inducing soils too dry and too little evaporation, which allows the soil to warm too efficiently (Moberg and Jones 2004). This behaviour has been observed in our simulation. Future improvements in the simulation of surface air temperatures are thus likely to be dependent on improvements in the representation of convective processes and surface processes as well.

The analysis undertaken in this study does not systematically diagnose the physical explanation of model errors but it suggests possible tracks for model improvement. Despite the systematic errors of the present-day climate simulation discussed here, the results are encouraging since dynamical downscaling techniques are the most reliable tool to estimate future projections of climate change with enough spatial detail, as needed for impact studies. However, results of future regional projections of climate change should be taken with care, since, even in the ideal case of a perfect simulation of the present-day climate, the projections may still be inaccurate.

Although the regional model has improved the representation of the observed present-day climate over that in the driving GCM, it is important to keep in mind that the skill of the former is strongly influenced by the skill of the latter. A survey in the literature reveals that the size of the errors is similar in other regional climate simulations (Misra et al. 2003; Rojas and Seth 2003; Nicolini et al. 2002; Moberg and Jones 2004; Giorgi et al. 2004). However, further model development for the region should be focused on physical parameterizations of various sub-scale processes.

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References

Caya D, Biner S (2004) Internal variability of RCM simulations over an annual cycle. Clim Dyn 22:33–46

Chen F, Dudhia J (2001) Coupling and advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: model implementation and sensitivity. Mon Wea Rev 129:569–585

Christensen OB (1999) Relaxation of soil variables in a regional climate model. Tellus 51A:674–685

Dickinson R, Errico R, Giorgi F, Bates G (1989) A regional climate model for the western united states. Clim Change 15:383–422

Figueroa S, Satyamurti P, Silva Dias PL (1995) Simulation of the summer circulation over the South American region with an eta coordinate model. J Atmos Sci 52:1573–1584

Frei C, Christensen JH, Deque M, Jacob D, Jones RG, Vidale PL (2003) Daily precipitation statistics in regional climate models: evalution and intercomparison for the European Alps. J Geophys Res 108(D3):4124

Garand L (1983) Some improvements and complements to the infrared emissivity algorithm including a parameterization of the absorption in the continuum region. J Atmos Sci 40:230–244

Giorgi F (1990) On the simulation of regional climate using a limited area model nested in a general circulation model. J Climate 3:941–963

Giorgi F (2002) Dependence of surface climate interannual variability on spatial scale. Gephys Res Lett 29:2101, doi: 10.1029/2002GL016175

Giorgi F, Bi X, Pal J (2004) Mean, interannual variability and trends in a regional climate change experiment over Europe I. Present-day climate (1961–1990). Clim Dyn 22:733–756

Grell GA, Dudhia J, Stauffer DR (1993) A description of the fifth-generation Penn System/NCAR Mesoscale Model (MM5). NCAR Tech Note NCAR/TN–398+1A, 107 pp

Hong S, Pan H (1996) Non-local boundary layer vertical diffusion in a Medium-Range Forecast model. Mon Wea Rev 124:2322–2339

Hsie EY, Anthes RA, Keyser D (1984) Numerical simulation of frontogenesis in a moist atmosphere. J Atmos Sci 41:2581–2594

IPCC (2000) In: Nakicenovic N (Coordinating Lead Author). Emission scenarios, a special report of working group III of the intergovernmental on climate change. Cambridge University Press, Cambridge, p 599

Kain J, Fritsch J (1993) Convective parameterization for mesoscale models: The Kain-Fritsch scheme. In: Emanuell KA, Raymond DJ (eds) The representation of cumulus convection in numerical models. Amer Meteor Soc, Boston, pp 165–170

Kalnay E, et al (1996) The NCEP/NCAR 40-year reanalysis Project. Bull Am Meteorol Soc 77:437–471

Lenters JL, Cook KH (1995) Simulation and diagnosis of the regional South American precipitation climatology. J Climate 8:2988–3005

Leung LR, Qian Y, Bian X (2003) Hydroclimate of the western United States based on observations and regional climate simulation of 1981–2000. Part I: seasonal statistics. J Climate 16:1892–1911

Liang XZ, Li L, Kunkel K (2004) Regional climate model simulation of US precipitation during 1982–2002. Part I: annual cycle. J Climate 17:3510–3528

Liebmann B, Allured D (2005) Daily precipitation grids for South America. Bull Am Meteor Soc 86:1567–1570

Menéndez CG, Cabré MF, Solman SA, Nuñez MN (2003) Regional climate simulation over southern South America using MM5. In: 7th international conference on southern hemisphere meteorology and oceanography. Am Met Soc, Wellington, New Zealand, pp 59–61

Menéndez CG, Cabré MF, Nuñez MN (2004) Interannual and diurnal variability of January precipitation over subtropical South America simulated by regional climate model. Clivar Exchanges 29:1–3

Misra V, Dirmeyer PA, Kirtman BP, Juang HM, Kanamitsu M (2002) Regional simulation of interannual variability over South America. J Geophys Res 107(D20) doi: 10.1029/2001JD900216

Misra V, Dirmeyer PA, Kirtman BP (2003) Dynamic downscalling of seasonal simulations over South America. J Climate 16:103–117

Moberg A, Jones P (2004) Regional climate model simulations of daily maximum and minimum near-surface temperatures across Europe compared with observed station data 1961–1990. Clim Dyn 23:695–715

New MG, Hulme M, Jones PD (1999) Representing twentieth-century space time climate variability. Part I. Development of a 1961–1990 mean monthly terrestrial climatology. J Climate 12:829–856

New MG, Hulme M, Jones PD (2000) Representing twentieth-century space time climate variability. Part I. Development of a 1901–1996 mean monthly terrestrial climatology. J Climate 13:2217–2238

Nicolini M, Salio P, Katzfey J, McGregor JL, Saulo AC (2002) January and July regional climate simulation over South America. J Geophys Res 107(D20) doi: 10.1029/2001JD000736

Pal J, Eltahir E (2001) Pathways relating soil moisture conditions to future summer rainfall within a model of the land–atmosphere system. J Climate 14:1227–1242

Pope V, Gallani M, Rowntree P, Stratton R (2000) The impact of new physical parameterizations in the Hadley Centre Climate model. Clim Dyn 16:123–146

Räisänen J, Hansson U, Ullerstig A, Döscher R, Graham LP, Jones C, Meier HE, Samuelsson P, Willén U (2004) European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. Clim Dyn 22:13–31

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003) Global analyses of SST, sea ice, and night marine air temperature since the late nineteenth century. J Geophys Res 108:4407 doi: 10.1029/2002JD002670

Reynolds RW, Rayner NA, Smith TM, Stokes DC, Wang W (2002) An improved in situ and satellite SST analysis for climate. J Climate 15:1609–1625

Rojas M, Seth A (2003) Simulation and sensitivity in a nested modeling system for South America. Part II: GCM boundary forcing. J Climate 16:2454–2471

Saulo AC, Nicolini M, Chou SC (2000) Model characterization of the South American low-level flow during the 1997–1998 spring-summer season. Clim Dyn 16:867–881

Seth A, Rojas M (2003) Simulation and sensitivity in a nested modeling system for South America. Part I. Reanalysis boundary forcing. J Climate 16:2437–2453

Stephens GL (1978) Radiation profiles in extended water clouds: II. Parameterization schemes. J Atmos Sci 35:2123–2132

Stephens GL (1984) The parameterization of radiation for numerical weather prediction and climate models. Mon Wea Rev 112:826–867

Tadross M, Gutowski W, Hewitson W, Jack C, New M (2006) Southern African interannual and diurnal climate variability in the MM5 regional climate model. Theor Appl Climatol 86:63–80

Wang M, Paegle J (1996) Impact of analysis uncertainty upon regional atmospheric moisture flux. J Geophys Res 101(D3): 7291–7303

Xu H, Wang Y, Xie SP (2004) Effects of the Andes on Eastern Pacific Climate: a regional atmospheric model study. J Climate 17:589–602